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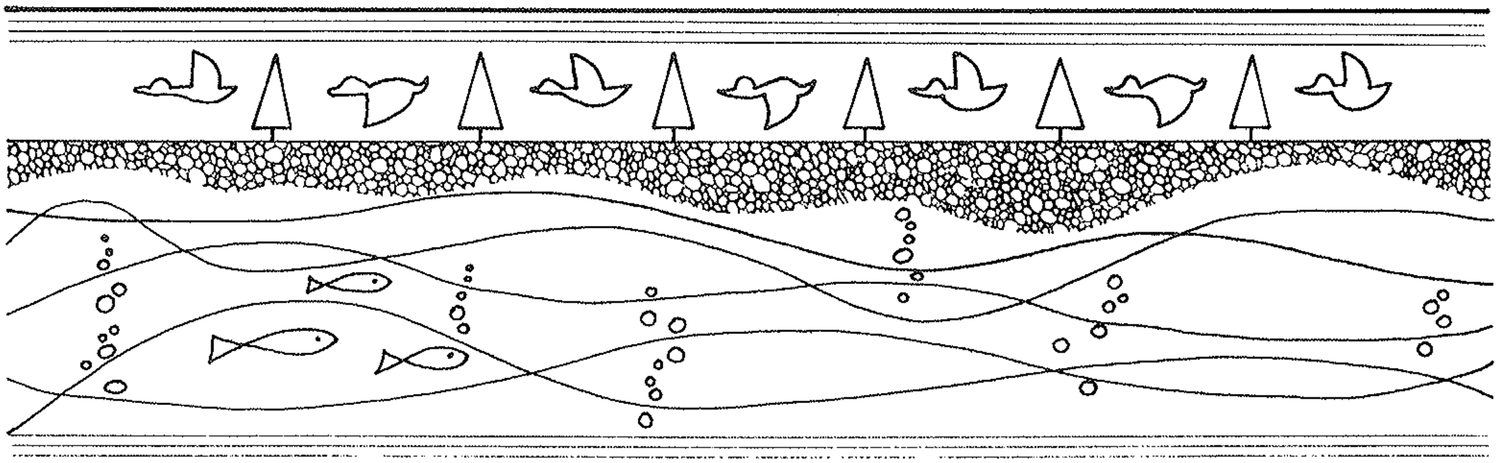

Table of Contents

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The Spill Technology Newsletter was started with modest intentions in 1976 to provide a forum for the exchange of information on oil spill countermeasures and other related matters. We now have over 2,600 subscribers in over 40 countries.

To broaden the scope of this newsletter, and to provide more information on industry and foreign activities in the field of oil spill control and prevention, readers are encouraged to submit articles on their work and views in this area.

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INTRODUCTION

This issue of the Spill Technology Newsletter contains two articles. The first, by Oistein Johansen, reviews the natural dispersion of oil under a slick. Mr. Johansen develops a model to describe this dispersion. The second paper by Ron Goodman and Merv Fingas, describes a program to develop methodologies to detect oil under ice. To date, the program has focussed on the use of acoustic and radio frequency systems.

DISPERSION OF OIL FROM DRIFTING SLICKS

Submitted by: Oistein Johansen
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INTRODUCTION

Present models for predicting the fate and behaviour of oil spilled at sea are based mostly on a simulation of the advective drift of the oil due to wind and currents. However, more sophisticated models are being developed which also take into account the various weathering processes. Such models are expected to give a more realistic assessment of the risk of impact from oil spills by including the loss of oil to the environment, through such processes as evaporation to the atmosphere and dispersion into water column. The physical aspects of evaporation are reasonably well established, while the mechanisms causing the vertical dispersion are poorly understood. The modelling of this loss is mostly based on an empirical approach, involving a sea state dependent dispersion factor or dissipation rate. More recently, several studies has been initiated in order to evaluate the dispersion loss based on theoretical considerations.

DISPERSION MECHANISMS

In recent years, the mechanism of dispersion of oil has been studied both experimentally and theoretically. The most common supposition is that breaking waves split the surface oil into droplets, which are mixed rather instantaneously into the water column. The further motion of these droplets is seen to be governed by a balance of the buoyancy of the oil droplets and the downward mixing effect caused by the turbulence in the water masses. The major parameters influencing this process are the terminal velocity of the oil particles, the level of turbulence and the initial mixing depth caused by the breaking waves.

The dispersion process which follows a breaking wave lends itself to a mathematical description in the form of a vertical diffusion-advection initial value problem.

When the initial concentration profile is established due to the effect of the breaking wave, the further development of the oil concentration profile may be assessed by the equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(D(z)\frac{\partial c}{\partial z}\right) + w\frac{\partial c}{\partial z} \qquad (1)$$

where c is the oil concentration,
D is the vertical eddy diffusion coefficient,
t is the time variable,
w is the terminal particle velocity,
z is the depth variable

This equation is assumed to be valid for a single class of oil droplets; the resulting concentration from a cloud of droplets may be determined by superposition of the results for a number of particle size classes.

In order to obtain realistic results from such a model, one must establish a number of conditions and parameters such as: the initial concentration profile relative to the wave breaking; the vertical eddy diffusion coefficient relative to depth and sea state; the initial particle size distribution relative to the quality and thickness of the surface oil; and the terminal velocity relative to particle size and density.

The terminal velocity of oil particles in water depends primarily on the dimensions of the particles and the density difference between water and oil as seen in Figure 1. The interfacial tension between oil and water may also play a role for larger oil droplets.

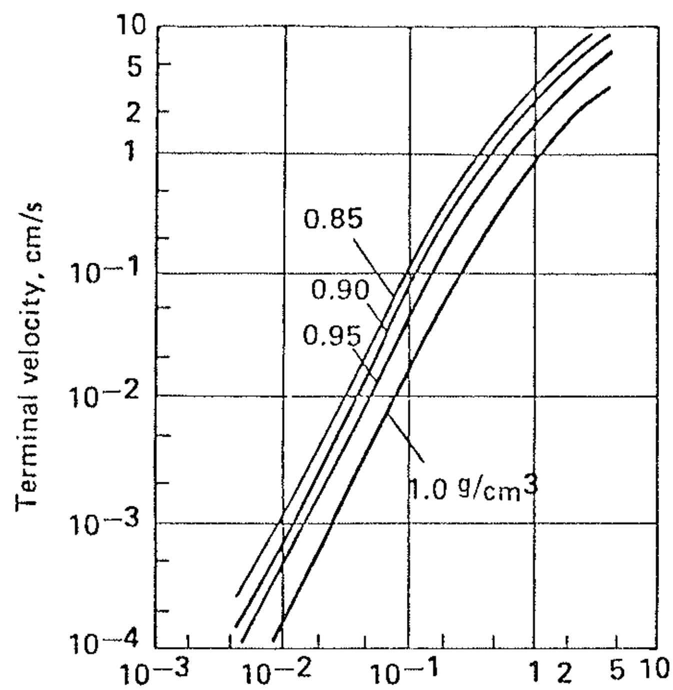


FIGURE 1 TERMINAL VELOCITY OF OIL PARTICLES OF DIFFERENT DENSITY IN SEA WATER WITH DENSITY 1.025 g/cm^3.

The results shown in Figure 1, which is chosen to correspond to the range of oil droplet sizes observed under real oil spills (Forrester, 1971), demonstrate that the behaviour of submerged oil will be strongly dependent on the size distribution of the oil particles mixed into the sea by breaking waves. Such information is, however, difficult to obtain, even under controlled laboratory conditions.

A survey reported by Forrester (1971) related to the grounding of the tanker ARROW gives some indication of the size range of submerged oil particles resulting from offshore oil spills. From the total number of samplings, Forrester concluded that the particle sizes were evenly distributed in terms of volume in the range from 10 to 1,000 microns.

The larger particles (0.1 - 1 mm) were observed to decrease in concentration with increasing depth; the concentration of the smaller particles seemed to be rather constant with depth. An attempt was made to relate the observed particle size distribution to the process of breaking up of larger oil particles into smaller by the action of turbulence. While this process may be of large importance in producing the particle size distribution immediately after a breaking wave event, it seems more reasonable to relate the long-term distribution to the combined effect of turbulent diffusion and resurfacing.

The mixing of surface oil into the water column by breaking waves is assumed to be an instantaneous process on the time scale considered for the total dispersion process. However, the moment when the dispersion phase takes over may not be a well defined point in time. The concept of an initial concentration profile may be seen as a substitute for a more detailed analysis of the mixing phase. Laboratory studies of the mixing of oil into water by breaking waves indicates on the other hand that the concept has some experimental evidence. Naess (1981) concluded from his experiments that the initial concentration profile could be taken as a triangular profile decreasing almost to zero at a depth in the order of the wave height.

On the basis of these results, it seems reasonable to assume that the initial condition may be related to the sea state, in terms of a mixing depth derived from the average height of the breaking waves., Due to lack of information on the height distribution of breaking waves, the mixing depth has been taken to be a certain fraction of the significant wave height, assuming that the waves which are breaking generally are smaller than the significant wave height. This fraction is chosen to be 0.5. The significant wave height has been computed from the wind speed and fetch by the empirical correlations resulting from the JONSWAP-program (Hasselman et al., 1973).

The vertical diffusion coefficient may also be related to the sea state. The model by Ichiye (1967) relates the diffusion coefficient to the wave parameters and includes the variation with depth (Figure 2).

Figure 3 illustrates the depth variation of the diffusion coefficient derived from the same models. Taken in this normalized form, the results are found to be relatively insensitive to the sea state; the depth variation may thus be expressed as a single function of a relative depth.

Using Ichiye's model, the diffusion-advection equation may be reduced to a normalized form:

$$\frac{\partial c}{\partial t'} = \frac{\partial}{\partial z'} \left(f(z') \frac{\partial c}{\partial z'} \right) + w' \frac{\partial c}{\partial z'} \qquad (2)$$

where

	$t' = t\, D(0) / Z^2$	Normalized time
	$z' = z / Z$	Normalized depth
	$w' = wZ / D(0)$	Normalized terminal velocity
	$f(Z')$	Normalized depth variation of the diffusion coefficient

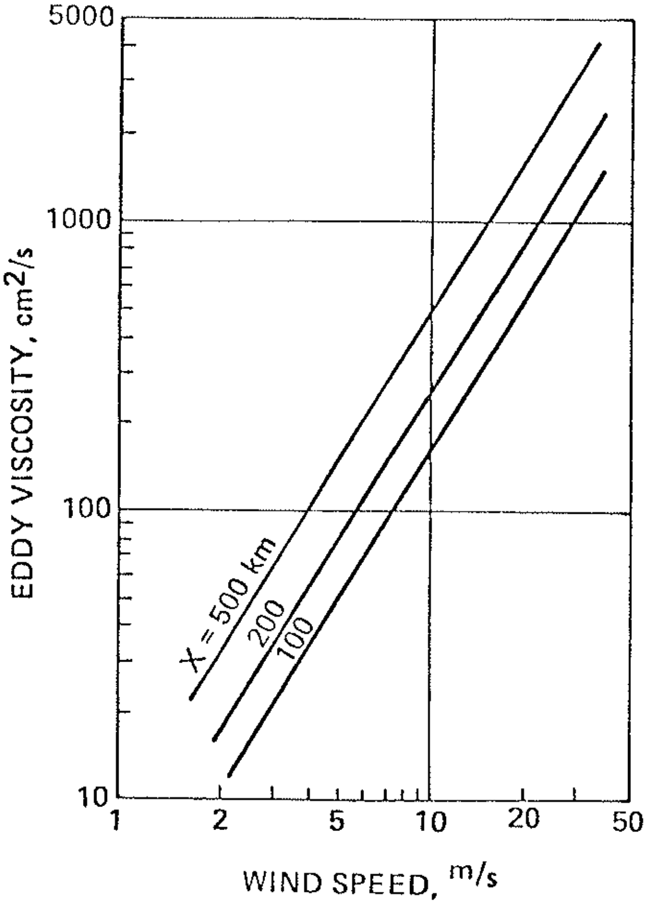


FIGURE 2 VERTICAL DIFFUSION FACTOR VERSUS WIND SPEED AT DEPTH $z = 0$, BASED ON ICHIYE'S MODEL AND JONSWAP CORRELATIONS FOR WAVE HEIGHT AND PERIOD.

This normalized equation has been solved numerically by a finite difference method. The time development of the concentration profile for a selected range of normalized terminal velocities is shown in Figure 4. Both time and depth are expressed in terms of normalized variables.

The graphs illustrate the changing importance of the process of advection and diffusion, respectively, as the normalized terminal velocity increases. For small terminal velocities, the dominating process is seen to be diffusion, since the penetration depth increases with depth. At large terminal velocities, the penetration depth decreases with time, indicating that advection is the dominating process.

The volume of submerged oil as a function of time has been determined by integrating the concentration profile with respect to depth. Results are shown for a range of normalized terminal velocities (Figure 5).

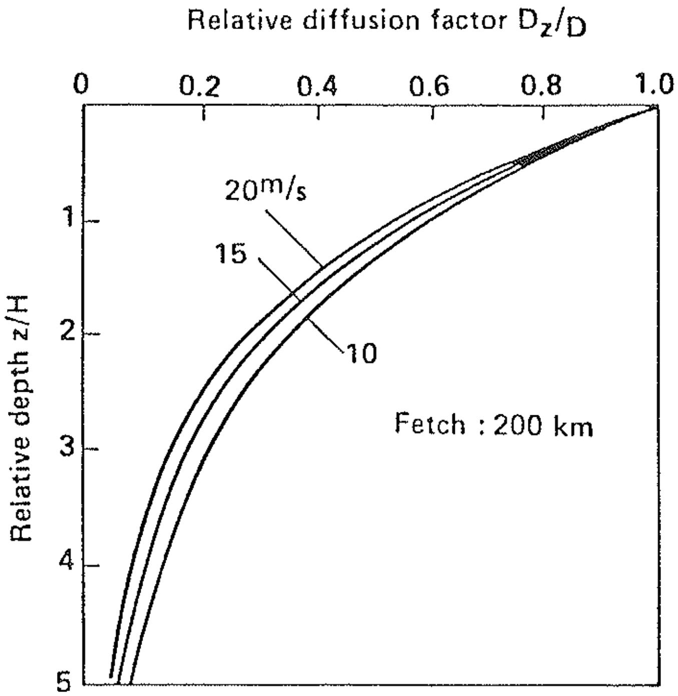


FIGURE 3 VARIATION OF THE VERTICAL DIFFUSION FACTOR WITH DEPTH.

The time development of the submerged oil volumes is found to be quite similar for all terminal velocities, differing only by a certain time factor. By defining a residence time as the time elapsed when a certain small fraction of the initial oil volume is remaining, and by scaling the time variable by this residence time, the family of curves for variable terminal velocities may be transformed into a single curve:

$$V(t') = V(t'/\,t'') \qquad (3)$$

where t" is the residence time for a given normalized terminal velocity.

By analysing the results obtained for the range of terminal velocities shown in Figure 5, functional relationships are obtained both for the residence time t" with respect to the normalized velocities, and for the submerged oil volumes with respect to the scaled time variable (t'/t") (Johansen, 1982). It is then possible to compute the time development of the submerged oil volume following a breaking wave event for any particle size. For a given particle size distribution, the corresponding development may be computed by integrating the values for all particle size classes over the particle spectrum.

ACCUMULATION OF OIL BELOW A DRIFTING SLICK

In the open sea, the wind-driven current is known to change with depth both in terms of a reduction of its strength and an increasing deviation in direction relative to the wind. The drift of submerged oil will therefore also deviate from the surface drift both with respect to speed and direction. For the present purpose, this effect will be represented by a simple two layer approach, i.e. as a surface and subsurface drift, both expressed in terms of the wind vector:

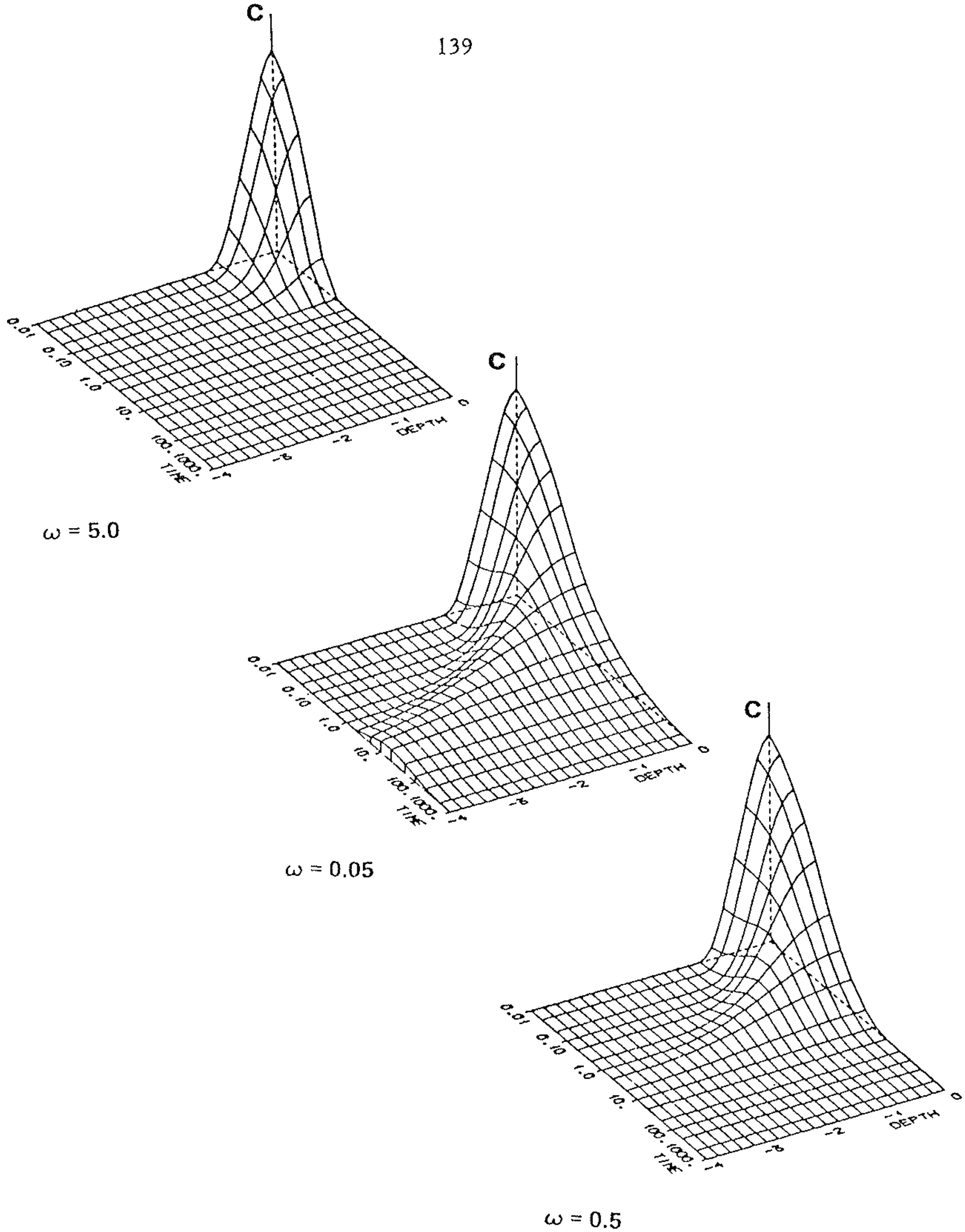


FIGURE 4 TIME DEVELOPMENT OF THE CONCENTRATION PROFILE AFTER A BREAKING WAVE EVENT FOR DIFFERENT TERMINAL VELOCITIES.

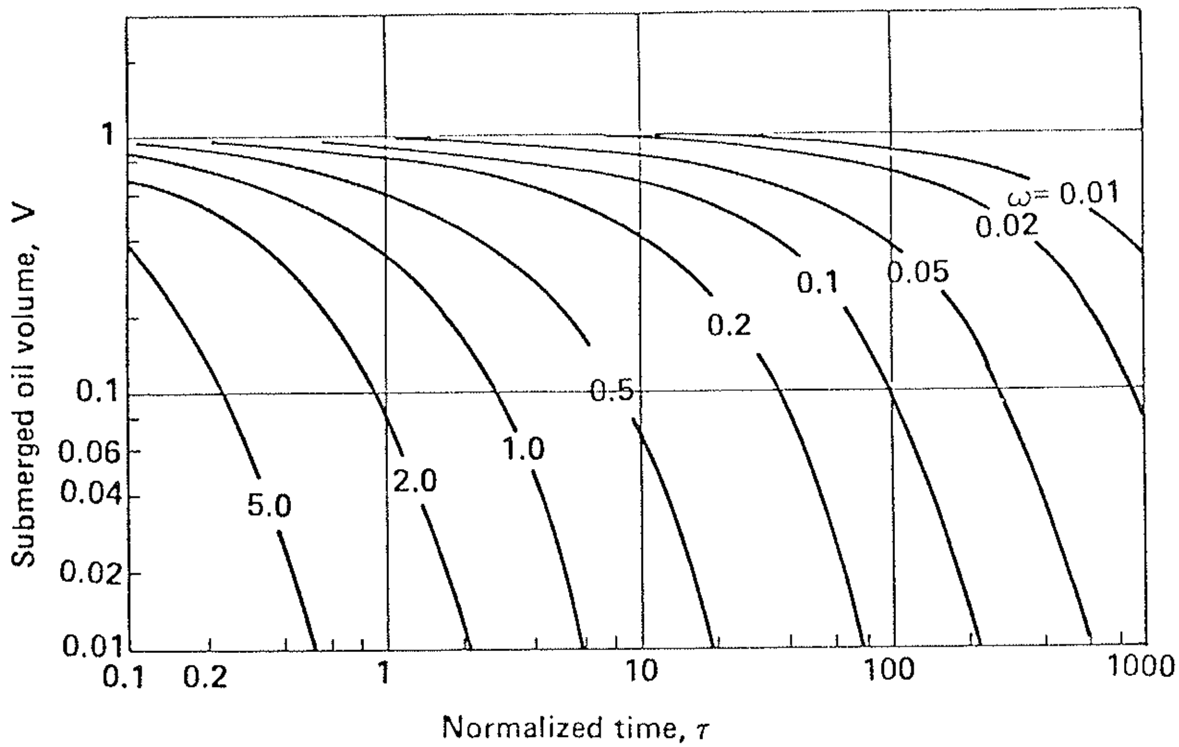


FIGURE 5 TIME DEVELOPMENT OF THE SUBMERGED OIL VOLUME AFTER THE EVENT OF BREAKING WAVE FOR A RANGE OF TERMINAL VELOCITIES.

- Surface drift: 3 percent of wind speed, turned 15 degrees to the right.
- Subsurface drift: 1.3 percent of wind speed, turned 45 degrees to the right.

A similar approach has been applied recently to study the effect of spreading of oil due to wave action (Haug, 1981).

The relative velocity between the surface and subsurface drift can then be expressed by the vectorial difference between the two. For a constant wind speed of 10 m/s, this will amount to about 20 cm/s in a direction close to the direction of the wind. The following discussion is based on this relative drift, and the motion of the surface oil is relative to stagnant water masses.

Repeated wave breaking in a drifting slick will cause oil to accumulate in the water masses. Assuming that the waves are breaking at constant time interval Δt, the accumulated volume after n successive wave breakings may be expressed as:

$$W(n) = V(n)\, v(0) + V(n-1)\, v(1) + \ldots + V(0)\, v(n)$$

which implies:

$$W(n) = SUM(i=0,n) (V(n-i) v(i)) \quad (4)$$

where n is the number of breaking waves,
V(j) is the oil volume mixed into the sea by wave number j,
v(j) is the fraction of the oil volume remaining submerged at time j t after the breaking event

If the volume mixed down by each breaking wave is constant, the summation may be replaced by an integral:

$$W(t) = \frac{V}{\Delta t} \int_{o}^{t} v(t')\, dt' \quad (5)$$

The factor before the integration sign represents the entrainment rate, and may be evaluated on the basis of the relative area covered by breaking waves, i.e. the white cap coverage, and the mean wave period. For a given surface oil concentration, the entrainment rate is expressed as:

$$\frac{V}{\Delta t} = Q \frac{P}{T} = Q\, v \quad (6)$$

where Q is the surface oil concentration,
p is the white cap coverage,
T is the mean wave period,
v = p / T, is a relative entrainment rate

The whitecap coverage is known to be related to the sea state. It seems generally accepted that white capping will occur in open sea as the wind speed exceeds 5 to 7 m/s. Above this sea state, observations reveal a large spread in the percent coverage (Figure 6). A simple linear relationship has been chosen to represent these data:

$$p = K\, (U - 5), \text{ percent} \quad (7)$$

where U is the wind speed, m/s,
K is an adjustable factor

The factor K may be chosen to represent the upper, medium, or lower portion of the spread shown in Figure 6. In the following, K is set to a medium value, i.e. K = 0.1.

When the surface oil concentration changes with time, equation (5) may be assumed to be valid for short time increments where the changes are small. This implies a discrete representation of the variation in the surface oil concentration, where:

$\bar{Q}(i)$ is the mean surface oil concentration in the time interval from t = (i-1) dt to t = i dt, and dt is the chosen time increment.

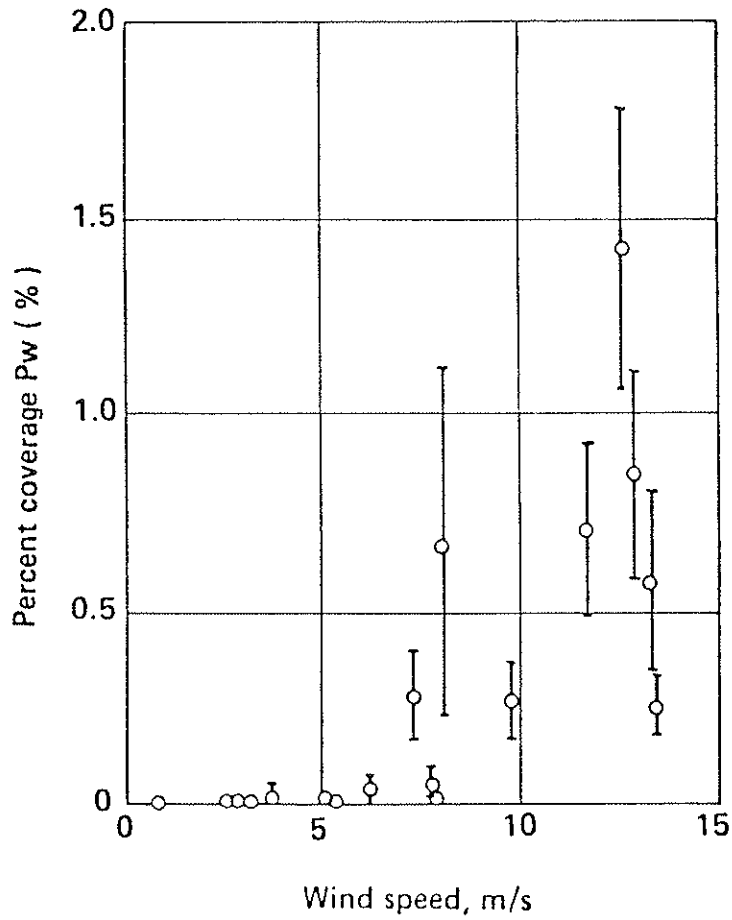


FIGURE 6 WHITE CAP COVERAGE VERSUS WIND SPEED (summarised from Cardone (1969)).

The accumulated oil volume at time t=n dt may then be expressed as:

$$W(n) = \bar{Q}(n)\ w(1) + \bar{Q}(n-1)\ w(2) \dots + \bar{Q}(1)\ w(n)$$

which implies:

$$W(n) = SUM(i=1,n)\ (\ \bar{Q}(n+1-i)\ w(i)\ ) \qquad (8)$$

$$\text{where } w(i) = \int_{t-dt}^{t} v(t')dt'$$

In order to utilize the above results, the change in the surface oil concentration with time must be determined. Neglecting other effects such as evaporation, the rate of change of the surface oil volume in a stagnant system will be due to the balance between the entrainment and resurfacing rates:

$$\frac{dQ}{dt} = - v\, Q + R \qquad (9)$$

where R is the resurfacing rate

This differential equation may be represented by a finite difference equation suitable for numerical solution:

$$Q(n) - Q(n-1) = - v\, \bar{Q}(n)\, dt + R(n) \qquad (10)$$

where

$\bar{Q}(n)$ is the average surface oil concentration during the period t-dt to t, t=n dt,
R(n) is the volume resurfaced during the same period

The resurfaced oil volume may be expressed by the sum of the changes in the submerged oil volumes:

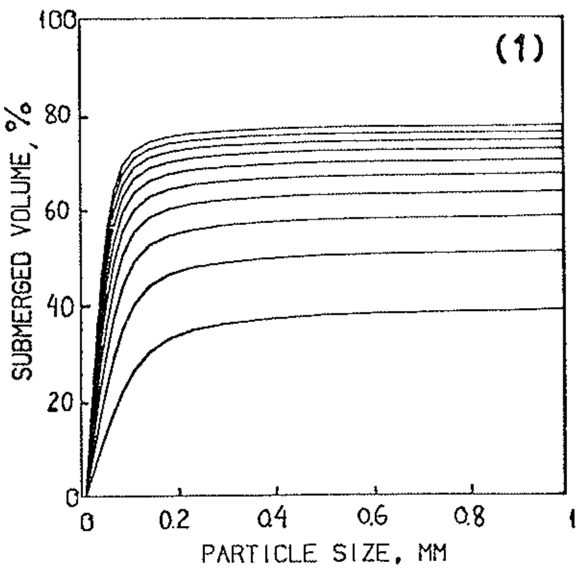
$$R(n) = SUM(i=1,n) \; (\; \bar{Q}(n+1-i)\; r(i) \;) \qquad (11)$$

where r(i) = w(i-1) - w(i)

Figure 7 shows the time development of the accumulated submerged oil volume for two different choices of particle size distributions, based on the approach presented above. In the first case, the distribution of the particles produced by the wave breaking is assumed to be even, i.e. each particle class is assumed to occupy the same volume. In the other case, the volume occupied by each particle class is assumed to follow a half-normal distribution with respect to the particle size. In both cases the wind speed is taken as 10. m/s, the oil density is 0.85 g/cm^3 and the particle size range is within 10 to 1,000 microns. The standard deviation of the half-normal distribution is chosen as 0.3 mm. The results illustrate the distribution of the submerged volume represented as the cumulative volume up to the largest particle size, where the value corresponds to the total submerged volume.

As expected, the case with an even distribution is found to produce a large submerged oil volume which is dominated by small particles. The case with the half-normal distribution produces a much smaller submerged volume, where the particle sizes are more evenly distributed. The computations also indicate that the total submerged volume tends to reach a stage of saturation at the end of the computed period, further changes with time being rather slow. This seems to contradict the observed steady dissipative loss of oil from slicks found in real oil spills.

In the present analysis, the slick is assumed to drift with a constant speed u relative to the underlying water masses. The slick is divided in elements of constant length dx in the direction of the relative drift, and the timestep is chosen to obtain a drifted distance equivalent to the element length in one timestep, i.e. dt = dx / u. The following difference equation is chosen to represent the combined effect of advection, entrainment and resurfacing:



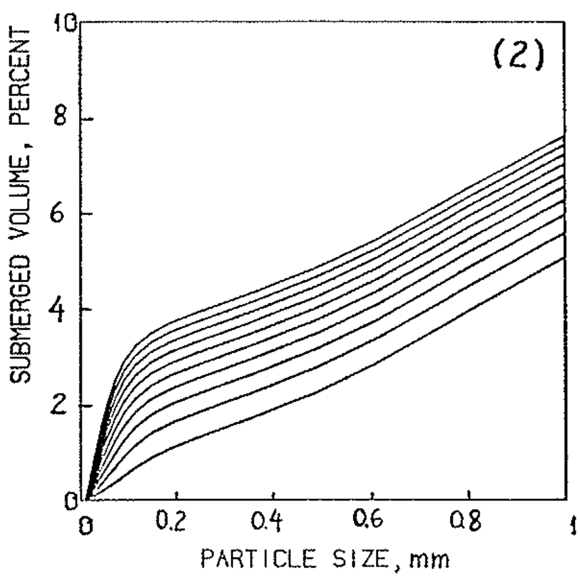


FIGURE 7 PARTICLE SIZE DISTRIBUTION IN SUBMERGED OIL. EXAMPLE COMPUTATIONS OF ACCUMULATED SUBMERGED OIL VOLUME FOR TWO DIFFERENT INITIAL PARTICLE SIZE DISTRIBUTIONS. LINES DRAWN FOR CONSTANT TIME INCREMENTS OF 1.4 HOURS UP TO 14 HOURS FROM START.
Case 1: Even distribution
Case 2: Half-normal distribution, std. = 0.3 mm

$$Q(j,n) - Q(j-1,n-1) =$$

$$- v\, Q(j-1,n-1)\, dt + R(j,n) \qquad (12)$$

where j refers to the element number, each element with a horizontal extension $dx = u\,dt$

Figures 8 and 9 demonstrate the time development of the surface and subsurface oil volumes for slicks with initial length of 1 km and constant surface oil concentration at the start of the drift period. In the first case, i.e. with an even initial particle size distribution, the surface oil is found to dissipate rapidly and the oil remaining at the surface is spread over a large area compared to the length of the original slick. At the end of the period concerned, 65 percent of the original slick is submerged. In the second case, i.e. with a half-normal particle size distribution, the submerged volume at the end of the period is found to be considerably smaller, amounting to only 6.5 percent. The spreading of the surface oil is also less, but the change in the spatial distribution is quite apparent.

Compared to the cases discussed previously, the time developments of the total surface and subsurface volumes, are found to be quite similar. However, due to the drift of the oil slick relative to the underlying water masses, a certain fraction of the resurfaced oil does not hit the original slick. This fraction will form an extension of the slick in the form of a thin oil layer. Such a behaviour is well documented from experimental oil spills. The most popular explanation of the phenomenon seems to be the assumption of a higher drift velocity of the thick oil lens compared to the thin regions of the slick, based on the fact that the thin slick always trails the lens of thick oil (NN, 1976).

It seems reasonable to assume that oil mixed into the sea from this thin slick will form particles with a different size distribution, i.e. a distribution dominated by small particles. In the previous examples, the particle size distribution formed by breaking waves was taken to be the same independent of the amount of oil at the surface. In the following example, the previous point has been taken into account by assuming two different size distributions, i.e. a half-normal distribution for the thick portion, and an even distribution for the thin portion of the slick. The distinction between the two categories is chosen arbitrarily at 30 percent of the original surface volume.

The time development of the total surface oil volume obtained in the last case is compared to the results from the two previous cases. The results of the computations demonstrate an increase in the loss of surface oil as compared to case 2 where the half-normal size distribution were used in the total length of the slick. The loss rate computed on the basis of the remaining surface oil volume was found to be quite steady over the period concerned in case 1; amounting to about 3 percent an hour.

CONCLUSIONS

The dispersion of oil from drifting slicks assumed that the mixing of oil into the water masses is caused by the action of breaking waves, while the further development in time of the entrained oil volume is determined by the combined effect of the buoyancy of the oil particles and vertical turbulent diffusion. On this basis, a model for the time development of the vertical concentration profile has been derived. From a set of

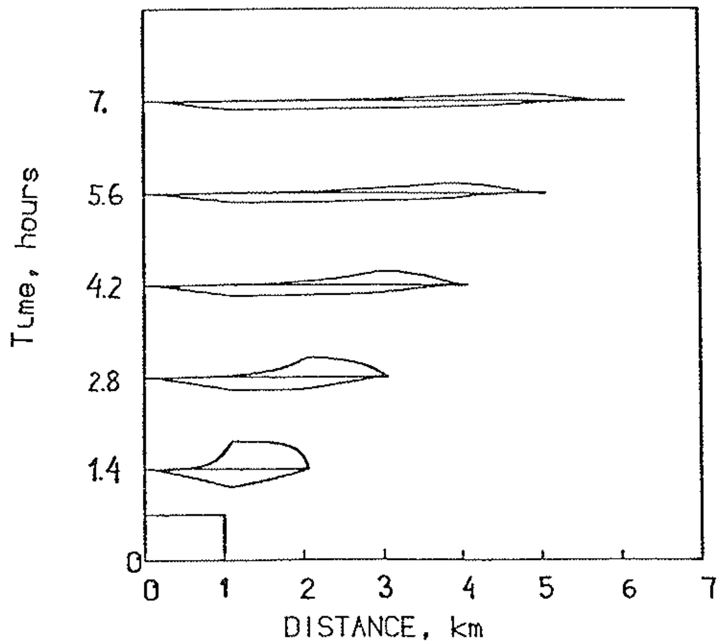


FIGURE 8 DRIFTING SLICK AT WIND SPEED 10 M/S. SURFACE AND SUBSURFACE OIL VOLUMES AT CONSTANT TIME INTERVALS UP TO 7 HOURS DRIFT TIME. EVEN INITIAL PARTICLE SIZE DISTRIBUTION.

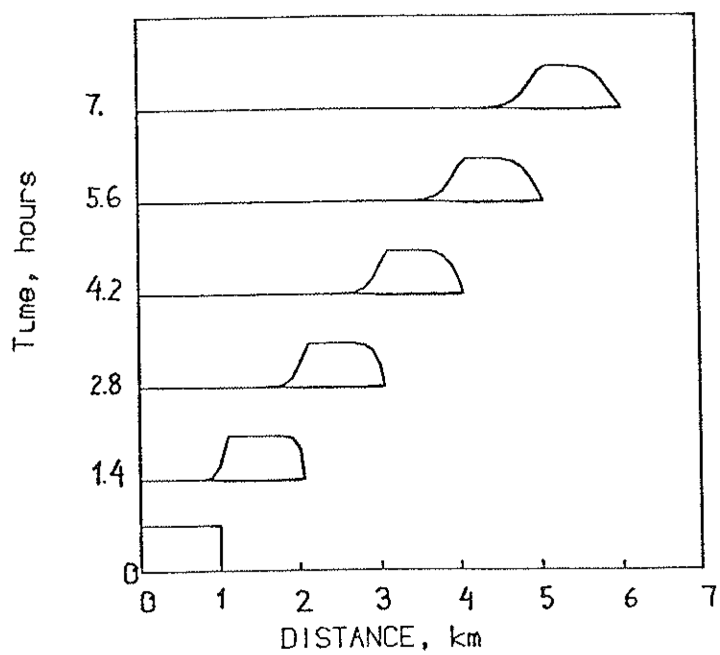


FIGURE 9 DRIFTING SLICK AT WIND SPEED 10 M/S. SURFACE AND SUBSURFACE OIL VOLUMES AT CONSTANT TIME INTERVALS UP TO 7 HOURS DRIFT TIME. HALF-NORMAL INITIAL PARTICLE SIZE DISTRIBUTION.

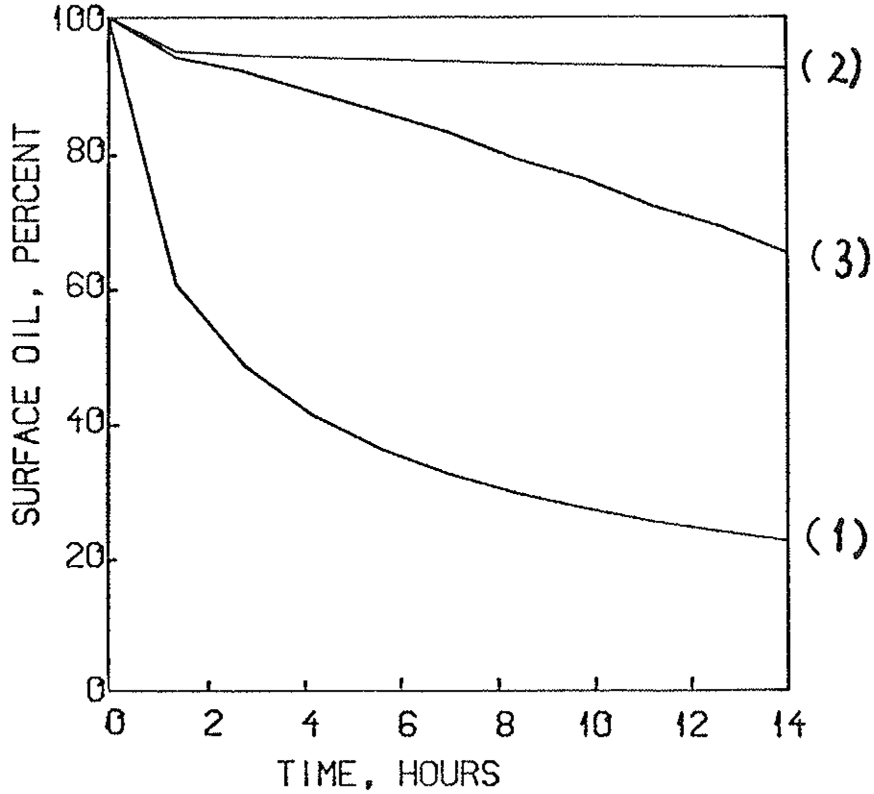


FIGURE 10 DRIFTING OIL SLICK AT WIND SPEED 10 M/S. TIME DEVELOPMENT OF THE SURFACE OIL VOLUME.
Initial length 1 km.
Case 1 and 2 as previously.
Case 3: The particle size distribution in the thick portion of the slick is taken as half-normal, while the size distribution in the thin slick is taken as even.

computations for a wide range of parameters, the decay of the submerged oil volume following the event of a breaking wave has been expressed in functional form in terms of the terminal velocity and the vertical diffusion coefficient.

Expressions for the terminal velocity in terms of droplet size and properties of the oil, as well as the vertical diffusion coefficient in terms of wind speed, were chosen from the literature. On the basis of these expressions, and the relationship derived for the decay of the submerged oil volume, the problem of successive wave breaking in drifting slicks was studied.

The study was initiated by an analysis of the loss of oil due to dispersion in stagnant slicks. An expression for the entrainment rate caused by successive wave breakings was formulated in terms of the white cap coverage and the mean wave period. Literature data of the white cap coverage, and expressions for the wave parameters in terms of wind speed provided the remaining basis for a complete approach to the problem of accumulation of oil under a stagnant slick.

The study was then extended to the case of drifting slicks by assuming a relative motion of the surface oil and the water masses below the slick. The surface drift and the drift of the submerged oil were both related to the wind, but with different drift factors and angular deviations relative to the wind vector. By including the contribution from advection, the effects of successive entrainment and gradual resurfacing were shown to form the characteristic extension behind the main slick in the form of a tail of thin oil, as observed in well documented experimental oil spills.

The spatial distribution of the surface and submerged oil was shown to be strongly dependent of the initial size distribution of the oil mixed into the sea by breaking waves. The size distribution which seemed to correspond most closely to the observed behaviour was found to be a half-normal distribution, dominated by large particles. However, example computations showed that a different particle size distribution had to be assumed for the thick and thin region of the slick in order to explain steady dissipative loss observed in real oil spills.

The larger fraction of small particles in the oil entrained from the thin region causes a higher loss rate from this region as compared to the region with thick oil. The thin tail thus serves as a kind of sink for oil which escapes the main slick.

In total, the approach seems to fill out several gaps in the understanding of the mechanisms of dispersion. The next step in the study will be to implement the model described above in a large-scale oil drift and fate model, in order to improve the predictions of the dissipative loss of oil.

ACKNOWLEDGEMENTS

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DETECTION OF OIL-UNDER-ICE - A JOINT ESSO/EPS PROJECT

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INTRODUCTION

Studies conducted as part of the Beaufort Sea Project (NORCOR, 1975) have demonstrated that oil deposited under ice would become encapsulated in the ice for significant periods of time, moving with the ice and rising to the surface of spring melt pools. Experiments have shown that it was only necessary to monitor the ice in order to track the oil. A system of micro and macro buoys recommended by an early AMOP program, has been developed (McGonigal and Wright, 1977; Roddis, 1980) and is routinely used for ice motion monitoring.

However, oiled ice could become separated from the buoys if the ice floes should break or diverge, as might occur in the shear zone. It's relocation would require the capability to detect the presence of oil in or under the ice. Such a system would also enable the routine monitoring of subsea under-ice pipelines and the detection of pollution near northern loading terminals and production platforms. The difficulties of detecting pipeline leaks under ice were identified as a concern of the Norman Wells Environmental Assessment Review Panel. This paper presents a background and overview of the limitation of oil-under-ice detection systems and indicates possible improvements.

Detecting oil-under-ice is related to the more general problem of measuring ice thickness. Both acoustic and electromagnetic sounders have been successful. Electromagnetic ice thickness equipment operating between 100 and 1,000 MHz is routinely used. However, the problems of coupling acoustic energy into the ice are severe and ultrasonic systems have not been used to a great extent as yet.

In order to detect oil-under-ice, the sensing radiation must penetrate the ice. A study, financed by industry and government under the auspices of the Environmental Protection Service, was commissioned to determine the feasibility of several oil-under-ice detection techniques (Gill, 1979). A number of methods, including radio frequency and acoustic echo systems and the use of gamma rays, were examined. The Environmental Protection Service also supported an unsolicited proposal (Remotec, 1979) to undertake a laboratory study of these sensors using both fresh and saline ice in a laboratory flume. A comparison was made between signal returns from the ice with and without oil at the ice-water interface. Sensors used were a GSSI radar, normally used for ice thickness measurement, a passive VHF radio spectrometer, a passive gamma ray spectrometer, and an ultrasonic inspection unit.

Except for the ultrasonic inspection unit, none of these sensors gave a significantly different signal with oil present at the ice-water interface. The ultrasonic system, operating at frequencies between 0.5 and 2.25 MHz, gave different returns when oil was present under freshwater ice. The Remotec report does not speculate as to the nature of the return signal or its origin. The acoustic impedance of oil, ice and seawater are similar, hence only a weak reflection should occur at these interfaces. The lack of signal difference for the impulse radar was unexpected. Several experiments have indicated that such radars could detect the presence of oil under some conditions (Dickens and Buist, 1981; Goobie et al., 1981; Mann, 1979; Gill, 1979; Kovacs, 1977). The cause of this reflection was not determined, and the authors did not quantify the conditions under which the signal would be observed. The time resolution required for a 1 cm thick layer of oil is four orders of magnitude shorter than that of the impulse radar systems. The strength of signal return at the ice-oil interface differs from that at the ice-water interface by an order of magnitude. The ice-water reflection coefficient approaches unity for seawater because it is a conductor.

Since the oil will naturally move to areas of reduced ice thickness (Cox and Schultz, 1981), another possible interpretation of the reported impulse radar results is that the ice was thinner where the oil was present, giving an anomalous signature. The oil fills the under-ice cavities, thus creating a smooth, flat reflector when compared to the ice-water interface. As demonstrated by Beckman and Spizzichino (1963), an enhancement in return signal of at least a factor of 10 can occur for an infinite reflector as compared to a reflector with a roughness amplitude in the order of a few wavelengths. Gill (1979) proposed that the effect was due to a phase shift at the interface when an insulator was present, since oil and seawater differ in conductivity by six orders of magnitude. The existing systems are not capable of measuring such a phase shift, which has a time scale of a few nanoseconds. As with acoustics, the exact process involved in generating different return signals from the ice-oil and ice-water interfaces is not understood.

A study by Rice University (Rivet, 1981) under the sponsorship of Exxon, indicated that the fluorescence spectrum of oil can be readily distinguished from that of natural sea ice. Using a 22 cm thickness of natural sea ice from Alaska, the laser-induced fluorescence spectra of oil and oil-under-ice were seen to be similar in character, with the ice causing only attenuation in signal strength. The results of these experiments show that the laser will penetrate up to 2 m of ice. The laser fluorescence and acoustic techniques are not adaptable to remote sensing aircraft; they are therefore limited to ice surface use.

In 1980, Esso Resources Canada Limited (ERCL) and the Environmental Emergency Branch (now the Environmental Emergencies Technology Division (EETD)) of the Environmental Protection Service entered into an agreement to jointly continue research in methodologies to detect oil-under-ice. The remainder of this paper describes this work. The mechanism of acoustic return from the ice-oil interface, the cause of the impulse radar returns, and the development of a practical system to detect oil-under-ice still must be resolved.

ACOUSTIC SYSTEMS

Jones and Kwan, (1982), demonstrated, as a result of a theoretical and laboratory study, that transverse waves can be propagated by the ice-oil interface, whereas they are not transmitted by the ice-water interface. The oil is much more viscous than the water, thus accounting for the transmittal of the transverse or shear waves. The reflection coefficient of the compressive wave is about the same for the two interfaces; techniques for separating the two waves must therefore be developed. Since shear waves travel at about half the velocity of compressive waves, they should be readily distinguished by an analysis of the time delays. Figure 1 illustrates hypothetical signal returns.

The ultrasonic flow inspection equipment used by Remotec (1979) operated at frequencies of 0.5, 1.0 and 2.25 MHz and succeeded in penetrating the ice. Jones and Kwan (1982) noted that frequencies give good spatial resolution, enabling the detection of thin films, while low frequencies propagate better through the ice. A frequency in the region of 100 kHz was found to be a good compromise between spatial resolution (about 3 cm) and attenuation.

In order to separate the compressive and shear waves, one must estimate the time delay (Figure 2). The minimum working thickness for vehicle traffic on ice is about 30 cm; the required time resolution is therefore in the order of 0.2 ms, or 20 cycles at 100 kHz. Since the capability of a transducer to respond is proportional to Q of the output circuit, this implies a low Q system, which in turn means a broadband ouptut signal. In order to receive such a pulse, a wide band receiver with its intrinsic poor signal-to-noise ratio would be necessary. Noise causes interference with the timing, and reduces the ability to discriminate between compressive and shear waves. Jones and co-workers at Dalhousie have developed a special transducer which, when operated at a low pulse-repetition rate (500 pps), does not ring and can be used to discriminate between the compressive and shear waves.

ELECTROMAGNETIC SYSTEMS

An impulse radar would seem to be the most likely system for detecting oil-under-ice. It has a demonstrated capability to measure ice thickness and is the only technique that would offer an airborne remote sensing capability (Dean, 1981).

The relevant properties of the various materials involved in the oil-under-ice problem are summarized in Table 1. In order for an interface to be detected, there must be a significant difference between the dielectric constants of the materials or their conductivity. The physical placement of the various layers is critical in order to achieve an adequate return signal.

As with acoustic systems, penetration of the ice and generation of a unique return at both the oil-ice and ice-water interfaces must be considered. Most radar systems have a system performance of about -100 db, so for a 2 m ice sheet, the attenuation should be less than 25 db/m. This implies a cold, low salinity ice such as is typical of the Arctic region. In order to achieve adequate spatial resolution, wave length (g) should be between 3 and 10 cm, thus electromagnetic sensors operate at frequencies between 300 and 1,000 MHz. Attenuation as a function of frequency is shown for various types of sea ice (Figure 3). Freshwater and multi-year ice are seen to give better results than first year ice due to their lower attenuation.

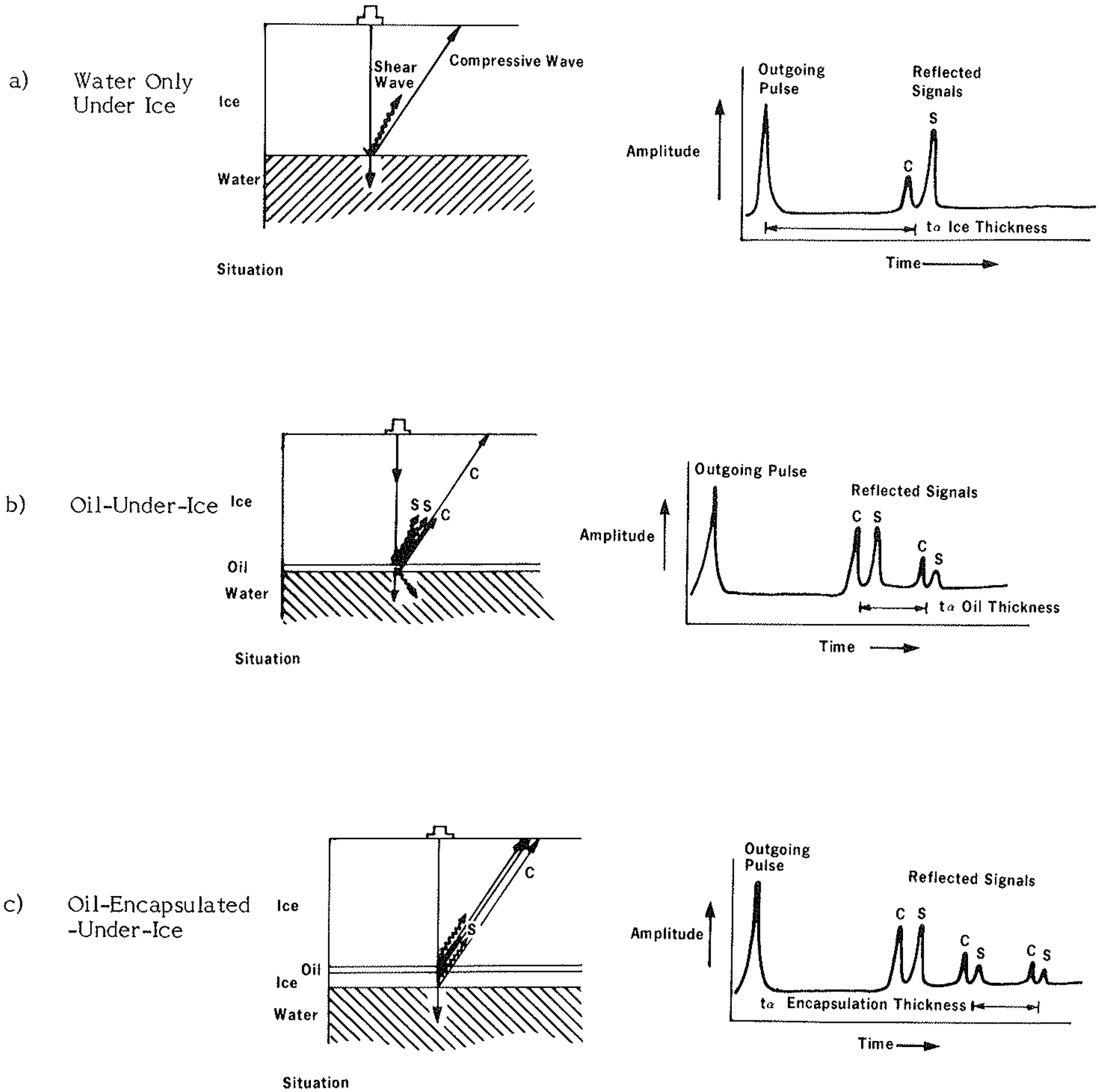
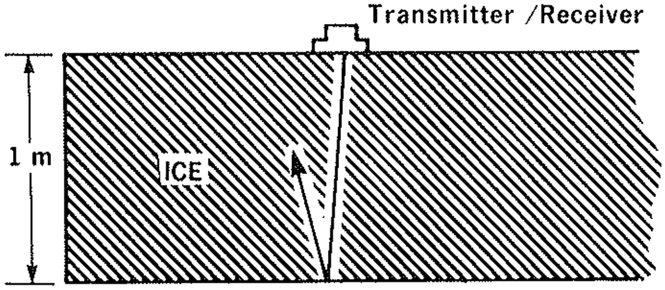


FIGURE 1 HYPOTHETICAL SIGNAL RETURNS

C = Compressive Wave
S = Shear Wave



Velocity of waves: 3,000 m/s compressive (3 m/ms) c
1,500 m/s shear (1.5 m/ms) s

Total transmit

$$tc = \frac{2t}{Vc}$$

$$ts = \frac{t}{Vc} + \frac{t}{Vs}$$

where t = time
v = velocity
c = subscript for compressive wave
s = subscript for shear wave

$$\Delta t = tc - ts = t\left(\frac{2}{Vc} - \frac{1}{Vc} - \frac{1}{Vs}\right)$$

$$= t\left(\frac{1}{Vc} - \frac{1}{Vs}\right)$$

$$\Delta t(ms) = t\left(\frac{1}{3} - \frac{1}{1.5}\right) = \frac{t}{1.5}$$

FIGURE 2 EXAMPLE OF TIME DELAY CALCULATION

TABLE 1 SUMMARY OF PROPERTIES RELEVANT TO THE RADIO FREQUENCY DETECTION OF OIL-UNDER-ICE (Dean, 1981; and present authors)

Media	Approximate Conductivity (siemens/m)	Approximate Dielectric (Constant)
Air	0	1
Freshwater	10^{-4} to 3×10^{-2}	81
Seawater	4 to 5	81 to 88
Freshwater Ice	10^{-4} to 10^{-2}	4
Seawater Ice	10^{-2} to 10^{-1}	4 to 8
Snow	10^{-5} to 10^{-2}	1 to 4
Oil	10^{-9} to 10^{-6}	2

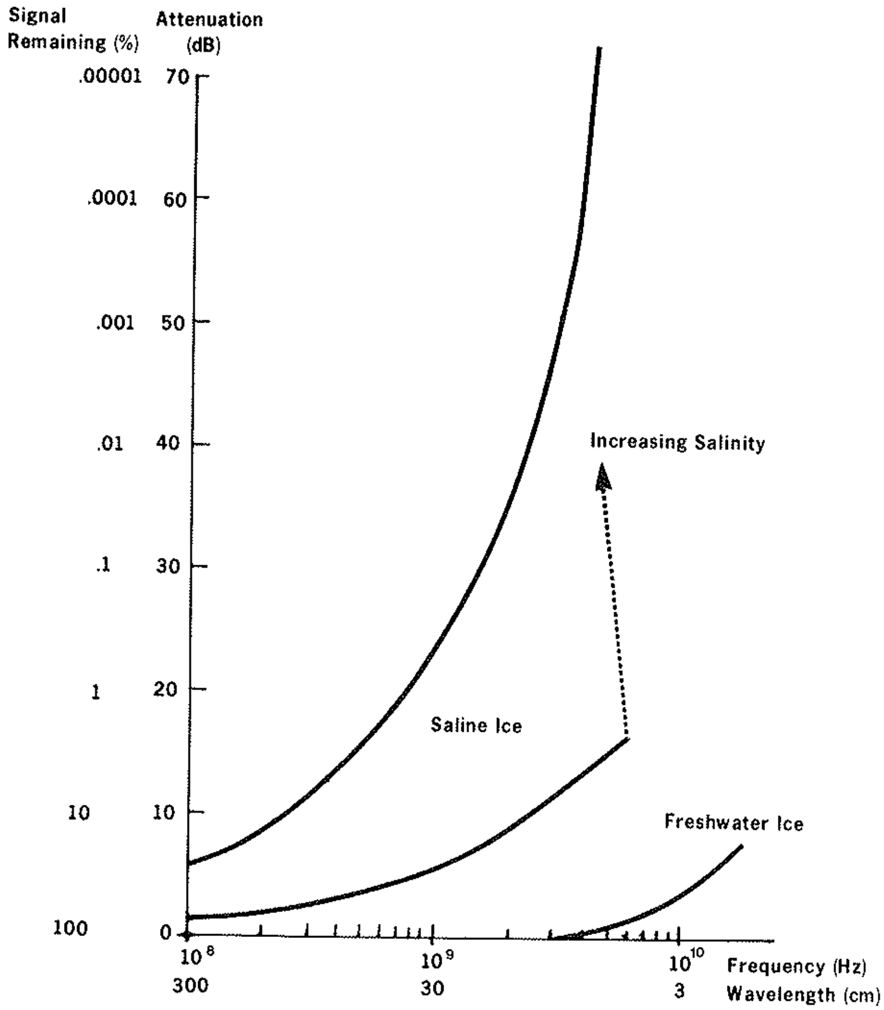


FIGURE 3 EXAMPLES OF ATTENUATION VERSUS FREQUENCY

Four types of signal return can be used to detect the presence of oil under ice:

a) out-of-phase returns due to the low conductivity of oil;
b) large amplitude returns due to construction interference effects;
c) spatial dependence of amplitude of return signals due to interference effects;
d) conductivity differences.

Phase measurement of these frequencies are difficult, since the times involved are in the order of nanoseconds. Dispersion and multipath returns could be confused with interface phase changes and thus render a unique interpretation impossible. While simple in principal, phase measurements are difficult.

The interference effects can be computed using a model in which the signals propagate across a series of plane dielectric layers. Each layer represents a potential surface

(Jackins et al., 1982) and the returns are a measure of the properties of the individual layers. By using an impulse radar and a fast-Fourier transform of the return signal, the layer structure can be determined.

Oil-under-ice can also be detected by measuring the spatial dependence of the return signal. The constructive and destructive interference patterns will be different when oil is present. Such effects have been noted on a vaster scale by glaciologists using radio echo sounding equipment (Robin et al., 1969).

CONCLUSION

In order, to detect oil-under-ice, one must understand the signal sources for both acoustic and electromagnetic radiation. The identification of the presence of shear waves in the return is a major advance. The use of resonant scattering theory is significant, but requires experimental verification. Electronic design problems with the acoustic systems must still be resolved. The ability to detect oil-under-ice is a needed technology and important advances have been made in the understanding of the problems, with identified signal sources that can detect oil-under-ice. We confidently hope that, in a few years, a reliable and practical system can be developed.

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